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NATIONAL BUREAU OF STANDARDS REPORT

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Report on Project 4881

Properties of Plastic Films for Use as
Waterproofing Materials in Underground
Heat Distribution Systems

by

A. G. Roberts

for

Office of the Chief of Engineers
Bureau of Yards and Docks
Headquarters U.S. Air Force



U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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Plastics Section
Organic and Fibrous Materials Division

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INTRODUCTION

A difficult problem in the engineering of underground heat distribution systems is the long-term sealing of the system against external water and moisture that can impair or destroy the heat barrier property of the insulation. Water can also cause serious corrosion to the heat carrying pipe, or to the outer metal shell often used in such systems.

In a typical heat distribution system conforming to present recommended^{(1)*} good engineering practice, the heat carrying pipe is surrounded by an adequate thickness of thermal insulating material held in place by a non-watertight wrapping which permits diffusion of water vapor from the insulation to a surrounding air space enclosed by a masonry or metal outer shell. Waterproofing of the outer shell against earth has generally been best accomplished by use of coal tar bitumastic materials. While these materials are excellent waterproofers as long as they remain in place, difficulties arise from their tendency to flow at elevated temperatures, such as might occur in the event of a heat pipe break or if seepage of external moisture reduced the insulating value of the insulation. Also, the adhesion of the bitumen (or other material) is sometimes poor because of the difficulty of obtaining in the field the cleanliness of surface required for good adhesion.

The use of tapes or sheet wrappings of pressure sensitive polyvinyl chloride or polyethylene sheeting materials has been considered an adequate alternative⁽¹⁾ to the use of the bituminous or other coating materials. Here also, trouble has been encountered because of the limitations of these plastic sheet materials at the elevated temperatures often met with in service and because of adhesion and bonding problems in the field.

The rapid technical advances that have characterized the plastics field raise the possibility that new plastic sheet materials may be developed, or may already be available, having improved properties making them more suitable for use as exterior waterproof membranes in heat distribution systems.

*Numbers in parentheses refer to the Bibliography at the end of this report.

To determine the present status of plastic film or sheet materials in relation to the waterproofing requirements of modern underground heat distribution systems, an extensive survey was made of the available literature and technical information on the physical and chemical properties of plastics. The results of this study are summarized in this report.

Asphalts, coal tar pitches, and impregnated felts, although good waterproofers within certain temperature limits, were outside the scope of the present survey on plastic films. Adhesives are considered only to the extent that they constitute essential adjuncts to the use of plastic film. Pressure-sensitive tapes, since they consist of a film plus adhesive, also are treated as secondary to the basic problem of developing a suitable film material.

Concise descriptions are given of the test methods generally employed in evaluating the properties of plastic films. Application techniques for plastic film materials are discussed. An extensive, selected bibliography is given.

Chief emphasis has been placed, however, on the most important properties of the plastic materials themselves. Indications are that among the new materials that have or will soon become available, there are several which give excellent promise of fulfilling, at reasonable cost, the rigorous requirements of application in underground heat distribution systems.

PROPERTIES OF FILM MATERIALS

The film properties considered to be of greatest importance for the intended application in underground heat distribution systems are as follows:

WATER RESISTANCE

- Water vapor permeability
- Water absorption

TEMPERATURE RESISTANCE

- Flow temperature or melting point
- Maximum service temperature (220°F required)
- Minimum service temperature (0°F required)
- Heat seal temperature

RESISTANCE TO SOIL CONDITIONS

Acids, bases, and salts
Fungi and bacteria
Rodents and insects

NATURAL WEATHERING RESISTANCE

Resistance to oxygen and ultraviolet radiation

STRENGTH

Tensile strength
Elongation
Bursting strength
Folding endurance

TOUGHNESS

Abrasion resistance
Puncture resistance
Tearing strength

ELECTRICAL RESISTIVITY

Volume resistivity

SPECIFIC GRAVITY or DENSITY

COST

In considering the above properties in relation to available plastics, it was possible immediately to eliminate a large number of materials as unsatisfactory, so that attention could be concentrated only on potentially suitable materials. Thus, thermosetting plastics in general were ruled out because of their rigidity and non-availability in film form. Elastomeric materials were not considered because rubber-like stretch is not an advantageous property in the present application. Among thermoplastic materials, the cellulose derivatives were eliminated either because of poor moisture resistance, poor fungal resistance, or poor resistance to elevated temperatures. Vinyl chloride-acetate copolymers are unsuitable because they soften at relatively low temperatures. Polyvinyl alcohol is soluble in water. Rubber hydrochloride film (Pliofilm) has a rather high water absorption and softens at moderately elevated temperatures.

After due consideration, the following types of plastics were selected as worthy of detailed study for purposes of their possible usefulness in underground heat distribution systems. Those marked with an asterisk (*) are new and highly promising materials:

- Polyester (Mylar)
- Polyethylene (conventional type)
- *Polyethylene (high-density type)
- *Polypropylene
- *Polycarbonate (Lexan)
- Polyvinyl chloride
- Vinylidene chloride-vinyl chloride copolymer
- Polychlorotrifluoroethylene (Kel-F)
- Polytetrafluoroethylene (Teflon)
- Polyamide (Nylon)
- Polystyrene
- Acrylonitrile-styrene copolymer
- Polymethyl methacrylate (Lucite or Plexiglas)

The important properties of the above materials are summarized in Table I. A discussion of the information developed during the data-gathering survey will now be presented, first from the viewpoint of the properties themselves, and then from the standpoint of the materials as they embody these properties.

PROPERTIES

Water Resistance

This is the fundamental property which is being sought in the present application. To have good water resistance, a material must combine the following basic factors: 1) insolubility in water, 2) low water absorption, 3) low water vapor permeability.

Insolubility implies that the material will not be attacked or degraded under conditions of continuous immersion in water.

Absorption of water into a plastics material causes swelling and often reduces strength through a plasticizing action. When the swollen material dries, shrinkage occurs. Alternate wetting and drying produces a swelling and shrinking cycle which constitutes a fatigue process that eventually weakens the material through rupture of polymer chains. Although the literature does not contain information about the resistance of specific materials to the effects of alternate wetting and drying, such as might readily occur in underground heat distribution systems, it is evident from the foregoing discussion that good durability in this respect would be associated with a low water absorption coefficient.

Low water vapor permeability is, obviously, a property of prime importance in a material to be used as a waterproofing medium. It should be noted, however, that this property does not necessarily go hand-in-hand with a low water absorption coefficient, or vice versa. Both properties must be independently assessed in evaluating the water resistance of the material in question.

It happens that many plastic film materials possess good water resistance, so that this property has not been a limiting factor for purposes of the present application in underground heat distribution systems.

Temperature Resistance

Resistance to elevated temperatures has been the property most difficult to obtain in plastic film materials. For use in underground heat distribution systems, the barrier film should be able to withstand temperatures up to 220°F without appreciable softening or deterioration. Temperatures this high, or perhaps even higher, might be reached in the event of a break in the high pressure steam pipe. In this circumstance, hot water and steam would pass through insulation, wrapping, and air space to the outer masonry or metal that is in contact with the plastic film.

Until recently, no practical plastic film material capable of continuous service at temperatures up to 220°F was available. Now, however, several suitable materials have been developed. They are described later in this report.

An important consideration in the elevated temperature behavior of a plastic film is its heat seal temperature. As will be further discussed, heat sealing promises to be a most effective way of bonding the plastic film or sheet into a sealed waterproof system. For this purpose, it is desirable that the film material be sealable at a temperature that it is practical to achieve with field equipment.

Maintainance of flexibility at low temperatures is also an important requirement of plastic films for the present application. Good handling and toughness properties are essential at least down to 0°F. Most of the plastic films considered here easily meet this requirement, and are in fact useful at temperatures far below this -- in some instances as low as -200°F.

Resistance to Soil Conditions

For good service underground, a plastic barrier film must be able to withstand many corrosive and destructive conditions⁽²⁾ present in the soil environment.

Acids and alkalies (strong bases) seldom occur in the free state in nature because of their great chemical reactivity, which results in salt formation. Salts, of course, abound in the earth's crust. In the presence of water, which is also abundant, these salts may yield an acidic or basic environment almost as destructive as that produced by the free acid or base. It follows that materials possessing good resistance to acids and bases will usually also have good resistance to salts. Many plastic film materials with good acid and alkali resistance are available and are described herein.

Moisture in the soil provides an environment which often supports the growth of fungi and bacteria that may attack plastics. Although many plastics are not in themselves susceptible to fungal attack and neither hinder nor support the growth of fungi, the materials with which the raw resins are compounded may be very susceptible. Plasticizers, for example, which often are incorporated into plastics (especially films) in substantial proportions to impart the requisite flexibility, may be highly susceptible to fungal attack. Destruction of the plasticizer can leave the film brittle and unusable, even though its resin base may be unharmed.

Although an extensive literature exists on the general aspects of fungal and microbiological deterioration⁽²⁾, reliable information on the resistance of specific materials is relatively sparse. In the procurement of film materials for use as moisture barriers in underground heat distribution systems, a fungus-resistant plasticizer should be specified. Ordinarily, the manufacturer should be able to supply such materials on the basis of available information. If not, then an experimental program should be carried out to obtain the necessary data. Incorporation of suitable fungicides can also contribute greatly to the durability of plastic films underground.

Although rodents and insects are capable of causing damage to plastic films^(3,4), there are few reports in the literature of rodent or insect damage to plastics underground, such as buried plastic pipe or buried plastic electrical insulation. Many insects that could harm plastics are not

found far underground. Termites, though voracious eaters, have a decided preference for wood cellulose and are not likely to be a hazard to plastic film underground. Rodents can gnaw through plastics in quest of food, but do not eat the plastics. Film around metal or masonry would not be a particularly attractive target. In rodent-infested regions, potential damage from these pests could be minimized by incorporating rodent repellents and rodenticides^(3,5) in the plastic film.

Weathering Resistance

Good weathering resistance, basically, stems from good resistance to oxygen and ultraviolet radiation. The presence of moisture is also an important factor in the deterioration of materials because of the profound effect which water exerts on so many chemical reactions. Ozone and corrosive dusts and droplets also have a deteriorative influence on many materials above ground. Below ground, many of the effects associated with natural weathering are minimized, but the corrosive action of water and oxygen remains.

Plastic materials differ greatly among themselves with respect to their inherent resistance to outdoor weathering. Thus methyl methacrylate plastic is almost immune to the effects of weathering over long periods of time, whereas polyethylene is quickly degraded outdoors unless stabilized. The words "unless stabilized" are the key to successful use of plastics outdoors. A great many special-purpose stabilizers have been developed for specific materials which have greatly increased the longevity and usefulness of plastics materials in outdoor applications.

Where plastic films intended ultimately for application in underground heat distribution systems may be exposed to sunlight during periods of storage in contractors yards or while awaiting sealing or burial after being applied to the heat distribution conduits, it may be desirable to provide the same stabilization as for outdoor applications in general, to assure the maximum durability. Effective stabilizers against ultraviolet light, oxygen, and heat are available for polyvinyl chloride, polyethylene, polyvinylidene chloride, and other plastic materials of interest in the present investigation.

Strength

Film strength, while secondary in importance to water and temperature resistance, is nevertheless an important property. Only those strength properties considered most relevant to the present application are listed in Table I.

Good tensile strength is of basic importance in any material that may be subjected to stress and strain during handling or service. A moderate elongation is desirable for ease in handling and fitting film materials, and for keeping stresses generated during installation or service at relatively low levels.

Bursting strength as given by the Mullen tester is of interest as a supplement to the tensile information. Values were not available for all the materials in the table.

Folding endurance, as given in Table I, was determined either with the M.I.T. tester (ASTM), or the Schopper bending tester. Although numerically the two methods are not directly comparable, they both give useful information about the fatigue strength of the material. Good fatigue strength may be an important attribute for resistance to the weakening effects of alternate wetting and drying.

Toughness

The property of toughness, while closely related to strength, implies certain additional qualities of particular relevance to abrasion resistance, puncture resistance, and tearing strength. From a theoretical viewpoint, toughness is often interpreted as the area under a stress-strain curve.

Data on toughness is given in Table I, where available. Some information on this property also appears in the discussion of the individual plastic film materials which is given later. Most of the materials considered in this report possess adequate toughness for the intended application in underground heat distribution systems.

Electrical Resistivity

All the plastic film materials described here possess a high electrical resistivity. Volume resistivity for the various materials ranges from 10^{12} to 10^{19} ohm-cm. Since good moisture

resistance was one of the prime criteria by which the most promising materials were selected, the volume resistivity of this group would not be expected to drop greatly even in the wet state.

Measurement of insulation resistance is a rapid, sensitive criterion of microbial attack on plastics⁽⁶⁾. Fungal attack can be indicated by a severe drop in insulation resistance before visual damage or strength loss become apparent. In many instances, however, visual growth on the specimen provides a reliable test⁽⁷⁾. In investigations of the breakdown of electrical equipment under high humidity conditions, a drop in insulation resistance has been attributed to moisture rather than to fungi^(8,9), the fungal growth being considered more as a warning of dysfunction than as deterioration in itself.

Specific Gravity

For practical purposes, the specific gravity (ratio of weight of material to weight of an equal volume of water at a given temperature) is numerically equivalent to the density expressed in grams per cubic centimeter, and both terms are used with equal frequency in the literature.

The specific gravity is useful not only as a measure of relative weight, but also as an indication of the yield per unit area to be obtained from a given weight of material made into a film of unit thickness, and as a means of following physical changes in a material or as a criterion of uniformity or purity.

Polyethylene and polypropylene are among the lightest of plastics materials.

Cost

Cost figures^(10,11) for the various plastic film materials are expressed in Table I both on a weight basis and in terms of the cost per 1000 square inches of a 1-mil thick film. In estimating the over-all cost of materials, however, a number of additional factors must be considered. Thus, some film materials may be used in a smaller thickness than others because they may be inherently stronger. Polyethylene terephthalate (Mylar) film, for example, is as strong in a 1/2-mil thickness as polyethylene film of 1 1/2-mil thickness. Application costs, whether by heat-sealing or adhesive, also influence the relative cost of materials.

Although the cost of some of the materials is prohibitive, as in the case of polytetrafluoroethylene (Teflon), others, such as high density polyethylene, are low enough in cost to be feasible for the present application. Still other materials, expensive at present because of their newness (e.g., polypropylene), may become economically practical with increased production.

MATERIALS

The various film materials will now be described individually, in terms of the properties that have been discussed:

Polyethylene Terephthalate (Mylar)

This is a relatively new material belonging to the polyester family of plastics. It possesses a combination of properties that makes it worthy of serious consideration for the present application in underground heat distribution systems. These properties include good water resistance, heat resistance to 300°F, and exceptional tensile strength, as well as good chemical resistance. Chief disadvantage of Mylar is its relatively high cost, about \$2.25 per pound; this cost can be offset somewhat by using it in the lower thickness permitted by its high tensile strength.

Bonding of polyethylene terephthalate can be accomplished with adhesives⁽¹²⁾ or by heat-sealing, although the latter is somewhat difficult and cannot be done by conventional means. A method using benzyl alcohol⁽¹³⁾ has been effective in heat-sealing Mylar. Also, Mylar can be laminated readily to other plastics, such as polyethylene⁽¹⁴⁾ or Saran⁽¹⁵⁾, to give combination materials possessing good heat-sealing characteristics as well as other enhanced properties.

A new amorphous type polyester film^(16,17), called Videne A, was recently announced by the Goodyear Tire and Rubber Company. It is serviceable from -40 to 200°F and is easily heat-sealed with conventional equipment. It becomes adhesive at 250°F and could be laminated to Mylar to impart good heat seal characteristics. It melts at 350°F, and is easily laminated to many other materials by heat and pressure. It possesses the greatest known abrasion resistance of any film surface -- even greater than that of melamine plastics. It is available, at present, only in limited quantities at \$2.25 per pound, but will be cheaper later as production is increased.

Polyethylene (conventional type)

Conventional polyethylene is produced by processes that yield a relatively low density material (0.92 g/cc) with a degree of crystallinity of 60-65 percent and only moderate heat resistance. Although possessing excellent moisture and chemical resistance, and low in cost, its maximum service temperature of 200°F is inadequate for the more severe temperature conditions that might be encountered in underground heat distribution systems.

Deterioration of polyethylene by sunlight (ultraviolet) occurs in only a few months outdoor exposure in the unstabilized material; however, by incorporation of suitable carbon-black pigments^(18,19), deterioration of polyethylene can be prevented for many years. Stabilization of polyethylene against heat is accomplished by incorporation of an antioxidant.

Most commercially available adhesives for polyethylene have low bond strength⁽²⁰⁾. Surface treatment with chromic acid improves its ability to be bonded with an adhesive. Polyethylene possesses excellent heat-sealing characteristics, however, and this is the preferred method of bonding it, both for ease and economy. Polyethylene is also easily welded, by techniques to be discussed later⁽²¹⁾.

Polyethylene (high-density type)

The new high-density polyethylenes that have come into prominence recently are superior to conventional polyethylene in many physical and chemical properties^(22,23). They are characterized by improved heat resistance, greater rigidity and tensile strength, increased puncture resistance and low temperature toughness, greater resistance to environmental cracking, and decreased permeability to gases and chemicals. Electrical properties remain excellent. Transparency is somewhat reduced. The improved properties of high-density polyethylenes may be attributed to their relatively high degree of crystallinity (about 80 percent) compared to that of conventional polyethylene (60-65 percent).

High-density polyethylenes are produced by new low pressure processes⁽²⁴⁾ made possible by the use of special catalysts developed by the Phillips Petroleum Company in the United States and by Dr. K. Ziegler in Germany. Both the Phillips and the Ziegler processes yield similar high-

density materials. The Ziegler process and properties of the Ziegler polyethylene are described in a number of articles in the literature^(25,26,27,28,29,30,31). Production of Ziegler-type polyethylene has been undertaken by a number of licensed manufacturers, including Farbwerke Hoechst producing "Hostalen"⁽³²⁾, Ruhrchemie making "RCH Polyethylene"^(33,34), Koppers Company with "Super Dylan"⁽³⁵⁾, and Hercules Powder Company with "Hi-fax"⁽³⁶⁾. The Phillips type, designated Marlex, is discussed in a bulletin⁽³⁷⁾ and in a paper⁽³⁸⁾. Both Phillips and Ziegler types are discussed in other articles^(22,24). A number of large manufacturers in the United States have obtained Ziegler licenses⁽³⁹⁾, including Du Pont, Bakelite, Monsanto, Goodrich, Gulf, Dow, and others, so that a tremendous production of high-density polyethylene can be expected in the near future.

Another type of high-density polyethylene ("Alkathene HD") is being made by I.C.I. by a modification of I.C.I.'s conventional high-pressure process in the same equipment and plants that make conventional high pressure polyethylene⁽⁴⁰⁾. The properties of this material lie between the Phillips and Ziegler low pressure types and the conventional high pressure type, but are much closer to the new low pressure (high-density) types.

High-density polyethylene is serviceable at temperatures up to 250°F or even higher. It has the excellent heat-sealing qualities of conventional polyethylene although the heat-seal temperature is about 50°F higher.

The excellent combination of properties possessed by high density polyethylene, including water resistance, elevated temperature resistance, ease of application, and low cost, make this material worthy of prime consideration for purposes of the present application in underground heat distribution systems.

Polypropylene

The polypropylenes are a new family of thermoplastics with unique and superior properties, beyond that of the high-density polyethylenes^(41,42,43). Polypropylene has exceptional heat resistance; it may be used up to 300°F. Its melting range is from 325 to 340°F. It can be fabricated by conventional techniques and yields a clear film heat-sealable with conventional equipment.

Although the polypropylenes promise to be reasonably priced when production increases, their present cost is high and quantities are limited. They are of great interest for the future but not yet ready for wide use in underground heat distribution systems.

Polycarbonate Resin (Lexan)

Polycarbonate resin is a new, tough, heat-resistant, dimensionally stable thermoplastic material^(44,45). It has been named "Lexan" by General Electric Company who developed it. Among its outstanding properties are low water absorption and heat resistance to 300°F. It can be cast or extruded into films or sheets (that are heat-sealable, or which can be welded with a hot air torch. Solvent cementing is also feasible.

The only adverse physical property of polycarbonate for purposes of the present application is its poor alkali resistance which might lead to attack and decomposition in some soil environments.

The present cost of polycarbonate is \$2.50 per pound in pilot quantities.

Polyvinyl Chloride

Among the older plastic materials, polyvinyl chloride has been widely used as a vapor barrier material, even in applications requiring elevated temperature resistance. Its maximum service temperature of 200°F is inadequate, however, for reliable performance under conditions that might be met with in underground heat distribution systems. Although resistant to oxidation, it is very susceptible to deterioration by heat and light unless stabilized^(46,47,48); fortunately, a number of effective stabilizers are available⁽⁴⁹⁾. Among the most effective heat stabilizers are heavy metal soaps, which react with the hydrogen chloride liberated during degradation and form harmless chlorides. The hydrogen chloride, if not removed, catalyzes further decomposition. Highly promising new stabilizers⁽⁵⁰⁾ will soon be available.

Polyvinyl chloride has excellent resistance to moisture and to chemicals that might be present in an underground environment. Its fungal resistance is good^(51,52). Rodent-repellent chemicals for vinyl chloride plastic⁽⁵³⁾ are available if required for use in areas where infestation of these pests might be a problem.

Polyvinyl chloride film can be bonded with special purpose cements (54) or by heat-sealing. A rapid method for bonding lengths of vinyl chloride plastic tubing in the field by the use of quick-fit couplings and a small torch has been successfully applied (55); it will be further discussed in the section on bonding methods.

Although polyvinyl chloride, like conventional polyethylene, has in the past been one of the best (but not completely adequate) materials available for the present application, both polyvinyl chloride and conventional polyethylene can now be supplanted with the new high-density polyethylene which promises to fulfill all the requirements for a vapor barrier in underground heat distribution systems.

Polyvinylidene Chloride-Vinyl Chloride Copolymer (Saran)

Saran is a tough, moisture-resistant material with generally good aging resistance and good resistance to fungi and bacteria (2). Like polyvinyl chloride it has limited elevated temperature resistance. Its heat-sealing properties are excellent.

It is a less desirable material than polyvinyl chloride for use in underground heat distribution systems because of its higher cost and its susceptibility to attack by ammonium hydroxide which may be generated in certain soil environments.

Polychlorotrifluoroethylene (Kel-F)

This material possesses properties that exceed the requirements of the present application (56). Since it is high in cost, and adequate cheaper materials are now available, the use of polychlorotrifluoroethylene in underground heat distribution systems is neither necessary nor desirable.

Polytetrafluoroethylene (Teflon)

This is an expensive premium material which far exceeds most of the requirements for use in underground heat distribution systems. It is mentioned here because of its uniquely superior chemical and physical properties (57, 58, 59) rather than for its practical usefulness in the present application. Although pressure-sensitive Teflon tape has been produced, the problems of bonding the material are formidable. Teflon is not heat-sealable.

Polyamide (Nylon)

Nylon is tough, abrasion-resistant, fungus-resistant, and resistant to strong alkali and most solvents, but it has a rather high water absorption and poor resistance to acids (2, 58, 59). Its maximum service temperature depends on the type of polyamide. It tends to oxidize at elevated temperatures. The poor water and poor acid resistance of nylon make it unsuitable for the present application.

Polystyrene

Polystyrene, while resistant to water and soil chemicals, is relatively more brittle than other thermoplastics and possesses only limited resistance to elevated temperatures (60). This latter limitation alone makes it an unsuitable material for the present application.

Acrylonitrile-Styrene Copolymer

This material, while possessing many useful properties, fails to qualify for use in underground heat distribution systems because of its relatively poor resistance to elevated temperatures (57).

Polymethyl Methacrylate

Polymethyl methacrylate film, like polystyrene, is relatively more brittle than most other thermoplastic film materials. It has superior resistance to outdoor weathering and is biologically very stable, being reportedly unattacked by fungi, bacteria, or insects (2). It has good resistance to water and to acids, bases and salts.

The usefulness of polymethyl methacrylate film in the present application is limited chiefly by its relatively poor physical strength at elevated temperatures.

Laminated Films

Many of the plastic film materials that have been discussed can be bonded to other plastics, fabrics, or metal foils to give a laminated film that possesses the desirable properties of both materials. The bonding can be accomplished with suitable adhesives or by heat and pressure. Thus, Mylar can be bonded to polyethylene or to Saran to combine the heat resistance and strength of the former with the heat-sealable

qualities of the latter. Or, polyethylene can be bonded to aluminum foil to increase the heat resistance of the former and the strength of the latter. A mirror of aluminum, deposited on a plastic film, could provide valuable heat reflective properties in some applications.

A laminate of high-density polyethylene and aluminum foil might well provide the ultimate in a moisture-proof, heat-resistant film for application in underground heat distribution systems.

Sources of Supply for Plastic Film

For information on manufacturers of plastic film materials, and on trade names of such materials, it is recommended that standard reference works, such as the Modern Plastics Encyclopedia (57) be consulted. The magnitude of such a list is beyond the scope of this report.

TEST METHODS

The more important test methods generally employed to evaluate the properties of plastic films will be briefly described in the following sections. For a detailed description of a given method, the bibliographic reference should be consulted.

In many instances a standard A.S.T.M. test is available. In other cases a Federal test method or a satisfactory commercial method is employed. For some properties, no standard procedure is available; for example, the heat-seal temperature is largely the consensus of information accumulated by manufacturers and fabricators concerned with this process.

Water Vapor Permeability

This property is usually measured by the procedures of ASTM Method D 697 (61). Two procedures are specified:

Method A. Desiccant Method: The desiccant (e.g., anhydrous magnesium perchlorate) is placed inside a test dish of specified size and shape. The specimen is placed over the opening of the dish and centered on the supporting ring or flange. A circular metal template with a beveled edge to which petrolatum has been applied is centered over the

specimen and dish opening. Molten wax, consisting of equal parts of beeswax and rosin, is flowed into the annular space around the beveled edge to seal the system. The template is removed as soon as the wax has cooled and solidified. The assembled test dish is weighed on an analytical balance and placed in an inverted position, so that the desiccant is in direct contact with the inner face of the specimen, on the test rack in a chamber maintained at constant temperature and relative humidity (73.4°F, 50% R.H.). A fan is used to maintain a current of air flowing over the exposed face of the test specimen. Weighings are made at intervals of several hours until a constant rate of gain is attained. Plotting weight increase against time gives a curve whose slope is a measure of the water vapor permeability.

Method B. Water Method: This differs from the desiccant method in that water is used inside the dish, which requires that the test be carried out with the dish in an upright position. Since there will be a layer of air between the surface of the water and the under side of the specimen, through which water vapor will diffuse at an undetermined rate, it is necessary to standardize on such factors as the ratio of water surface area to test area (should be 1:1) and the distance between the water surface and the under side of the film (should be 25 mm). The rest of the procedure is the same as for Method A.

Water Absorption

This property is measured in accordance with ASTM Method D 570 (62). Specimens 1- x 3-inches in size are conditioned by drying in an oven for 24 hours at 50°C, cooling in a desiccator, and weighing. The conditioned specimens are completely immersed in distilled water maintained at 23°C (73.4°F). At the end of 24 hours, the specimens are removed one at a time, all surface water wiped off with a dry cloth, and weighed immediately. If the specimen is 1/16th inch or less in thickness, it should be put into a weighing bottle immediately after wiping and weighed in the bottle.

When materials are known or suspected to contain appreciable amounts of water-soluble ingredients, they should be reconditioned again for 24 hours at 50°C and weighed. If this weight is lower than the original conditioned weight, the

difference is considered to be water-soluble matter lost during immersion and is added to the weight increase on immersion when computing the total water absorption value.

Tensile Strength and Elongation

Measurement of these properties of plastic films is usually made by ASTM Method D 882, Method B (63), in which a constant rate of jaw or grip separation is employed. The test specimen is a strip of uniform width and thickness and $\frac{1}{4}$ inches or more in length. The width of specimen should be chosen to allow failure to occur well within the load capacity of the machine. A rate of cross-head motion of 2 inches per minute is used for film with an ultimate elongation less than 100 percent, and a rate of 20 inches per minute for film with an ultimate elongation of 100 percent or more. Thickness and width are measured at several points and the minimum cross-section is recorded. Tensile strength is calculated by dividing the maximum load in pounds by the original minimum cross-sectional area in square inches.

While the specimen is being elongated, the displacement of initial gage marks on the specimen is followed with divider points. The percentage elongation is calculated by dividing the elongation at the moment of rupture by the original gage length and multiplying by 100.

Bursting Strength

Bursting strength as given in Table I was determined with the Mullen Bursting Strength Tester according to the procedure of ASTM Method D 774 (64). In this test, the specimen is clamped over a circular orifice beneath which is an extensible membrane that expands into the film specimen under steadily increasing hydraulic pressure applied to the system. The specimen is stretched into what approaches a hemispherical shape. The pressure in the system at the instant of rupture is indicated by a maximum-reading dial gage; this pressure is taken as a measure of the bursting strength of the specimen and is reported as Mullen "points" rather than psi, because the true bursting strength of the specimen involves other factors (for example, the distensibility of the specimen) in addition to the pressure in the system (65).

Tearing Strength

Two different methods are in general use for measuring the tear strength of plastic films:

(1) A.S.T.M. Method D 689, or the Elmendorf tear strength method, determines the average force in grams required to tear a sheet by measuring the work done in tearing a number of sheets together through a fixed distance after an initial slit of specific length has been made in the test specimen with a sharp blade (66). The testing machine is of the pendulum impulse type with a means for holding the pendulum in a raised position, a means for releasing it instantaneously, and a means for indicating the maximum arc through which the pendulum swings when released. The specimen is clamped in a plane perpendicular to the plane of swing of the pendulum. The difference in amount of swing with and without the specimen in the path of the pendulum provides a measure of the work done in tearing through it, as computed from the geometry and mass of the calibrated instrument.

(2) In A.S.T.M. Method D 1004, using a static-weighting method and a constant rate of grip separation, tear strength is determined by measuring the maximum load required to tear through a specially-shaped die-cut specimen, or through a bundle of such specimens, and is expressed as the pull in pounds per inch of thickness required to tear a single specimen (67). The specimen has a 90° off-set, rounded on the outer edge and forming a right angle at the center of the inner edge, so that a high stress concentration is produced at the center of the specimen when the load is applied. The tear strength value is therefore an indication of the notch sensitivity of the material as well as a function of its tensile strength, elongation, and shear strength. Where bundled specimens are employed to bring the tearing strength value within the range of the instrument, the thickness value for computation purposes shall be the average of the individual thicknesses of the sheets that make up the bundle, never the apparent thickness of the bundled specimen.

Volume Resistivity

Measurement of the electrical resistance of insulating materials such as plastics or plastic film, because of the very high resistance of such materials, is subject to large errors unless specialized methods are used. Suitable methods are described in A.S.T.M. D 257 (68). The details of the methods are too lengthy and complex for treatment here, except to consider the basic concepts and usefulness of the measurements.

The volume resistivity of a material is defined by the A.S.T.M. as the ratio of the potential gradient parallel to the current in the material, to the current density. In the metric system, the volume resistivity is numerically equal to the volume resistance when measured between two electrodes which cover opposite faces of a centimeter cube of the material. The volume resistance between two electrodes which are in contact with, or embedded in, a specimen is the ratio of the d-c voltage applied to the electrodes to that portion of the current between them that is distributed through the volume of the specimen.

The volume resistivity of an insulating material, such as plastic film, can provide an indication of the uniformity of processing of the material, detect traces of impurities that might affect the quality of the material, and indicate the existence of deterioration or foreign matter (e.g., fungal growth) in the material.

Specific Gravity

The specific gravity of a plastic film is measured by weighing it in air and when immersed in water. Details of the method are given in A.S.T.M. D 792 (69). A wire of suitable length is hung from the pan support of an analytical balance and tared. The specimen is then attached to the wire so as to be suspended about an inch above a pan straddle supporting a beaker, and the weight in air (a) is determined. The specimen, still suspended by the wire, is then immersed (by filling the beaker) in freshly boiled distilled water at the reference temperature, and the weight (b) again determined. Finally, the specimen is removed from the wire and the weight with the same length of wire immersed in the water is determined. The

specific gravity is calculated from the following formula:

$$\text{Sp. Gr.} = \frac{a}{a - b - c} \quad \text{where } c \text{ is the loss in weight of the wire on immersion.}$$

Folding Endurance

The procedure for measuring folding endurance with the Schopper tester is given in A.S.T.M. D 643, Method A (70). Test specimens are 15 mm in width and 10 cm in length. The ends of the specimen are gripped by two horizontally opposed clamps provided with calibrated spring tension which varies during the folding cycle as a slotted folding blade, through which the specimen is inserted, folds the specimen while the blade slides back and forth between creasing rollers. The specimen is folded at a uniform rate of approximately 120 double folds per minute until it is severed at the crease. The number of double folds required to sever the specimen is recorded as the folding endurance.

Method B of A.S.T.M. D 643 describes the procedure for use of the MIT Folding Endurance Tester. Experience (71) with this test method has indicated that it is not adaptable for testing all types of plastic films, particularly those of interest in the present investigation, such as vinyls, polyesters, and polyethylene. Therefore, data by this method have not been reported herein.

Weathering Resistance

Conditions for the exposure of plastic material to outdoor weathering are defined in A.S.T.M. Method D 1435, wherein are discussed the method by which the material is to be exposed, the general procedure to be followed, and the climatological information to be recorded (72). The method does not cover the methods of test to be used in evaluating the effects of exposure, except for visual appearance and dimensional changes. Specimens for exposure are mounted on racks at an angle of 45 degrees to the horizontal and facing true south. Racks are located at a variety of climatologically different test sites including temperate, arctic, desert, tropical, salt air, and industrial locations. The appearance and dimensions of the

specimens before weathering and after various periods of exposure are recorded. Other properties of the material, involving destructive tests, can be evaluated by exposing a sufficient number of specimens.

Artificial or accelerated weathering tests, although they do not provide a direct correlation with natural weathering, give a very useful indication of the type of outdoor service to be expected from a given material, and such tests are widely employed.

Recommended practice for an accelerated weathering test using the S-1 bulb and a fog chamber is given in A.S.T.M. D 795 (73), and also in Federal Specification L-P-406, Method 6021. Test specimens are mounted on a modified phonograph turntable operating at approximately 33 rpm beneath the S-1 bulb. Periods of radiation are followed by periods in a fog chamber. The radiation and wetting cycles for each 24-hour period are as follows: 2 hours in the fog box, 2 hours irradiation, 2 hours in fog box, and 18 hours irradiation. The duration of the test is usually 240 hours, although any length of time may be specified as circumstances warrant.

An artificial weathering test using fluorescent sunlamps and a fog chamber is described in A.S.T.M. D 1501 (74). The test is performed in an enclosure in which a turntable and five fluorescent sunlamp bulbs are installed, so that the specimens are three inches below the lamps. The fluorescent lamps employed must have been aged for at least 50 and not more than 1050 hours. The turntable operates at 30 to 40 rpm. Hot air at 55 to 60°C is blown over the specimens at a rate adequate for maintaining them at that same temperature. The fog chamber consists of a closed, shallow box with a spraying unit and baffle to prevent direct impingement of the spray on the specimens. The specimens are exposed continuously for 240 hours, unless otherwise specified, by repetition of the following 24-hour schedule: 2 hours fog, 2 hours ultraviolet radiation and hot air, 2 hours fog, and 18 hours ultraviolet radiation and hot air. A visual examination of the specimens is made after each step of the testing procedure. At the end of the test procedure, various optical and physical tests may be made on the specimens to evaluate the effects of the weathering process; such as, luminous transmittance, haze, flexural strength, etc.

Chemical Resistance

The resistance of plastics, including films, to acids, bases, salts, and other chemicals is determined by immersion in various standard reagents for 7 days at 23°C, or other specified temperature, as described in A.S.T.M. Method D 543 (75). The length, width, thickness, weight, and appearance of the specimens before and after the immersion period are noted. Specimens removed from the various solutions are wiped with a dry cloth and weighed immediately in a weighing bottle. The dimensions of the treated specimens are measured immediately after weighing.

Fungal Resistance

A variety of methods are used to evaluate the fungal resistance of plastics (6,7,76), including visual, optical, and electrical methods. The specimen is placed in a warm, humid environment and inoculated with any of a variety of fungal cultures. Visual observation of fungal growth is often an adequate test. In other instances, the microscope can be used to establish the existence of fungal attack. Measurement of insulation resistance is usually one of the most sensitive tests of fungal attack; fungi, and the moisture associated with them, can cause an enormous drop in insulation resistance even when visual indication of attack is completely lacking.

Abrasion Resistance

Information on the abrasion resistance of plastics in film form is not generally available in the literature. The Taber Abraser which, despite a number of drawbacks, is widely used to evaluate abrasion resistance (77), is not suitable for use on films. Several A.S.T.M. test methods (78,79,80) are available which can give information on abrasion resistance of plastics.

The Abrasive Jet Method (81) developed at the National Bureau of Standards, although designed for testing organic coatings, is well adapted for measuring the abrasion resistance of plastic films taped or bonded to a metal substrate; in fact, a film is used as a reference standard in calibrating the instrument. It gives a measure of abrasion resistance in

terms of the time required for a jet of fine abrasive particles to abrade through a unit thickness of film. Although data on a variety of films has not been obtained with this equipment, such information could be obtained if desired.

Insect and Rodent Repellents

Test methods for evaluating the efficiency of insecticides and insect repellents usually involve the use of those test insects most likely to do damage, and are conducted till death of all insects is obtained (88). For insecticides, a sample of treated material is given to the insect as its exclusive food, except for tap water. Usually the insects are paralyzed and die before even trying to eat the material. Repellents are tested in a 3-compartment box which requires the insects in a first compartment to walk or land on the treated material in a second compartment in order to reach food in a third compartment. A good repellent will keep the insects in their original compartment where they will die of starvation.

Rodenticides and rodent repellents are tested by using treated material as a partition to separate rats from food (88). Satisfactory rodenticides or rodent repellents will prevent even voracious recently-caught field rats from getting to the food.

A.S.T.M. Committee D-14 on Adhesives has prepared two methods that may be used to test plastic films. One is for determining susceptibility to attack by roaches (88a) and the other by laboratory rats (88b).

Other Test Methods

Other A.S.T.M. test methods, not directly utilized for the data given in Table I, but of some interest in connection with the properties of plastic films, include a heat distortion test (82), a method for measuring the tensile and elongation properties of bulk plastics (83), a method for determining brittle temperature (84), and several penetration or puncture resistance tests (85,86,87). Bacteria have also been known to attack some plasticizers in vinyl plastic films. A.S.T.M. Committee D-14 on Adhesives has developed a test method for determining the effect of bacteria which may be applicable (87a).

APPLICATION METHODS

In addition to possessing the required physical and chemical properties, a material for use in underground heat distribution systems should be capable of being applied by readily available techniques that can be relied upon to produce a complete and durable sealing of the system. Plastic films are available in the form of tapes, sheets, and rolls, in a variety of widths. Although application techniques will vary with the nature and form of the material, the general principles involved in applying plastic film materials can be given:

Tapes

Plastic tapes for the present application must be of the pressure-sensitive type. The tape is applied by wrapping it around the conduit in an overlapping spiral, while maintaining strong tension to provide the adhesive-activating pressure. The bonding efficiency of a pressure-sensitive material depends on the temperature; therefore, care must be taken to apply the material within the temperature range recommended by the manufacturer.

A possible serious limitation of pressure-sensitive tapes for the present application is the difficulty of formulating a pressure-sensitive adhesive that is efficient over the entire temperature range (0 to 220°F) in which it is expected to perform. The existence or non-existence of such a material was not established during the present survey. Considering the inherently difficult nature of the problem of formulating a material that must be tacky at 0°F and yet not flow at 220°F, it is believed that pressure-sensitive tapes are not the best materials for use in underground heat distribution systems.

Adhesive-bonded Sheeting or Film

In the form of discrete sheets or as continuous film from a roll, flexible plastic vapor barrier material can be applied around the conduit system and sealed with a thermoplastic adhesive that bonds overlapping ends of the material. A thermoplastic adhesive is specified because such an adhesive can closely approximate the properties of the film materials

under consideration here and is likely to better withstand the stresses developed during the expansion and contraction that will occur over the wide operating range of temperature to be encountered. Such adhesives dry by solvent evaporation, leaving the solid adhesive in place. The nature of the adhesive required is determined both by the temperature and other physical requirements of the application and by the nature of the material to be bonded.

The field of adhesion and adhesives, besides being too vast in itself for review in the time available for the present survey, is not directly relevant to the basic problem of a suitable plastic film. Since a plastic film with the requisite properties appears to be available, as mentioned elsewhere in this report, the development of a suitable adhesive should be largely a matter of applying the same knowledge in a modified form, and is a problem that may with confidence be entrusted to the experienced adhesive formulator.

For many of the film materials described in this report, proven adhesives are already available. A recent article by Riley (89) discusses the application techniques involved in solvent cementing, adhesive bonding, thermal welding, and mechanical fastening, and also gives tables of specific adhesives for particular applications. A report by Faunce (90) discusses test procedures and performance criteria for an adhesive for vinyl chloride plastic and for polyethylene barrier materials and describes a new neoprene-diisocyanate type adhesive that has proved effective. Information as to the suitability of certain adhesives for particular applications and their method of use is readily available from adhesives manufacturers.

The use of adhesives in the field requires careful surface preparation and cement application, besides involving fire and toxicity hazards. Considering the amount of work involved, the skill required, and the cost of adhesives in general, it is felt that adhesive-bonding of plastic film for the present application, while entirely feasible, is neither the easiest nor the most economical way of accomplishing the task. Instead, most serious consideration should be given to one of the several methods of heat-sealing plastic film which are described in the next section.

Heat-sealing Sheet or Film

Of the various methods available for bonding plastic film for underground heat distribution systems into a sealed system, the most promising from the viewpoint of economy and ease of application as well as efficiency of seal are the heat-sealing techniques. A rapid efficient system may be visualized in which continuous lengths of plastic sheeting or film are laid in the conduit trench before laying down the piping (or inserted under the piping if already installed) and then turned up and sealed in a continuous process with mobile heat-sealing equipment.

Polyethylene, including the high-density type so promising for the present application, is among the easiest of materials to heat-seal. In addition to lending itself to the conventional heat-sealing techniques, it can be welded using a heated air torch. The hot gas, produced by gas or electric heating within the torch, is directed against a round polyethylene filler rod and the sections to be joined (91). The welding proceeds at a rate of about 5 inches per minute.

The electronic welding of vinyl film is discussed in (92). An effective method for bonding lengths of vinyl chloride plastic pipe in the field, which may be applicable in cases where discrete sheets, after being sealed lengthwise, must be joined to other sheets, has been developed (55). In this method, the end of one length of tube is heated on the inside, with a small torch, to soften it, and the softened end is then stretched backwards over a ring previously placed around the tubing. The end of the other tube is then heated and pulled over the ringed piece, and a pressure yoke is pulled over the belled-out portion of the tubing to make a strong, waterproof seal.

Heat-sealing methods include flame, hot gases, hot wire (impulse heater), electronic high frequency, electrical (resistance) heating, hot metal band, etc. (59,93,94). In all heat-sealing methods, temperature, pressure, dwell time, and cooling time are all important. A recent study of the dielectric heat-sealability of films (95) makes use of an apparatus in which the various heat-sealing parameters can be closely controlled for a systematic study of their effects.

Of the various heat-sealing methods that are available, electronic high-frequency heating appears to offer the best promise for fast, efficient, and relatively economical use in the present application for sealing film in underground heat distribution systems. Mobile field equipment for generating the necessary RF power is available and could be put to effective use in the continuous sealing process envisioned in the first paragraph of this section.

Heat-sealing is used for bonding thin materials and welding for bonding thicker sheets. Thus, if it is decided to use sheeting that is too thick to heat-seal readily, welding can be used.

SUMMARY

An extensive survey of the literature on plastic film materials has been made to establish the suitability of such materials for use as exterior waterproofing membranes in underground heat distribution systems. Relevant properties of conventional plastic film materials and of promising new materials are tabulated and discussed. Test methods commonly employed for evaluating properties of plastic films are concisely described. Application techniques for plastic film materials are considered. A selected bibliography is given.

RECOMMENDATIONS

On the basis of the information developed during the literature survey on plastic films, and after careful study of the properties of a wide variety of films in relation to the performance requirements of underground heat distribution systems, it is recommended that prime consideration for the present application be given to the new high-density polyethylene materials. These materials have excellent water and chemical resistance, are serviceable from -105 to 250°F, possess good strength and toughness, are easily applied and heat-sealed, and are low in cost.

It is believed that high-density polyethylene film, applied as continuous sheeting which is turned up around the conduit and then heat-sealed in a continuous process by mobile sealing equipment, may offer an effective, rapid, and economical means for waterproofing underground heat distribution systems.

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TABLE I. PROPERTIES OF PLASTIC FILMS^a

<u>Property</u>	<u>A.S.T.M.^{b,h} Test Method</u>	<u>Polyethylene Terephthalate (Mylar)</u>
WATER RESISTANCE		
Water vapor permeability ^c	D 697	0.05-0.15
Water absorption, 24 hr., %	D 570	<0.5
TEMPERATURE RESISTANCE		
Flow temp. (melt. pt.), °F		482-490
Maximum service temp., °F		300
Minimum service temp., °F		-80
Heat seal temperature, °F		490 (coated)
RESISTANCE TO SOIL CONDITIONS		
Acids	D 543	Good
Bases	"	Good
Salts	"	Good
Fungi and bacteria		Inert
Rodents and insects ^d		
WEATHERING RESISTANCE		
Resistance to oxygen plus ultraviolet radiation	D 1435 (outdoor) D 795 (S-1 bulb) D 1501 (fluorescent)	Fair
STRENGTH		
Tensile strength, psi	{ D 882,	17000-24000
Elongation, %	{ Method B	35-110
Bursting strength (Mullen) ^e	D 774	45-60
Folding endurance	D 643, Method A ^g	20000
TOUGHNESS		
Abrasion resistance		
Puncture resistance		
Tearing strength, grams	D 689 ⁱ	10-27
" " , lb/in.	D 1004 ^j	650-1740
ELECTRICAL RESISTIVITY		
Volume resistivity, ohm-cm.	D 257	10 ¹⁹
SPECIFIC GRAVITY	D 792	1.38-1.39
COST ^f		
Per pound, dollars		2.25
Yield, sq. in. per lb. (1-mil thick film)		20000
Per 1000 sq. in., dollars		0.112

(continued on page 2)

TABLE I. (continued) - page 2.

<u>Property*</u> <u>(abbrev.)</u>	<u>Polyethylene</u> <u>(conventional)</u>	<u>Polyethylene</u> <u>(high-density)</u>	<u>Polypropylene</u>
WATER			
Perm.	0.04-0.08	0.02	
Absorp.	0-0.8		
TEMP.			
Flow	230	265-300	325-340
Max.	200	250-275	300
Min.	-70	-105 to -190	<14
Seal	200-375	250-400	
SOIL			
Acid	Excellent	Excellent	Excellent
Base	Excellent	Excellent	Excellent
Salt	Excellent	Excellent	Excellent
Fungi	Unaffected	Unaffected	Unaffected
Rodents			
WEATHER			
Oxygen + UV	Good if stabilized	Appears good	Probably good
STRENGTH			
Tensile	1100-3500	2500-6000	3900-5700
Elong.	50-800	10-1300	500-750
Burst	48		
Fold	Very high		
TOUGHNESS			
Abrasion			
Puncture	Excellent		
Tear, g	60-200		
" , lb/in.	65-575	600-1300	840-1000
ELEC. RESIST.			
Vol. resist.	>10 ¹⁵	>10 ¹⁵	>10 ¹⁶
SPEC. GRAV.	0.92	0.93-0.96	0.90-0.91
COST			
Per lb.	0.53	About 5%	Promises to
Yield	30000	higher than	reasonable
1000 sq. in.	0.018	conventional	

*See first page of table for full designation.

(continued on page 3)

TABLE I. (continued) - page 3

<u>Property*</u> <u>(abbrev.)</u>	<u>Polycarbonate^k</u> <u>(Lexan)</u>	<u>Polyvinyl</u> <u>Chloride</u>	<u>Vinylidene</u> <u>Chloride - Vinyl</u> <u>Chloride Copolymer</u> <u>(Saran)</u>
WATER			
Perm.	1.3×10^{-8}	0.35-2.0	0.01-0.03
Absorp.	0.3	Nil	Nil
TEMP.			
Flow	514		290-310
Max.	>300	200	200
Min.	-135	-50	-50
Seal		250-350	275-320
SOIL			
Acid	Fair	Excellent	Excellent
Base	Poor	Excellent	Excellent
Salt	Fair	Excellent	Excellent
Fungi		Good	Good
Rodents			
WEATHER			
Oxygen +UV	Appears good	Good	Very good
STRENGTH			
Tensile	9000-10500	1400-5600	1800-15000
Elong.	60-100	150-500	5-250
Burst		20-40	35
Fold		Good	>500,000
TOUGHNESS			
Abrasion		Excellent	Very good
Puncture			10->100
Tear, g		60-1400	80-465
" , lb/in.		110-490	
ELEC. RESIST.			
Vol. Resist.	2×10^{16}	10^{12} - 10^{14}	10^{13}
SPEC. GRAV.	1.20	1.23-1.29	1.68
COST			
Per lb.	2.50 in pilot	0.87	1.04
Yield	quantities	21500	16300
1000 sq. in.		0.040	0.064

*See first page of table for full designation.

(continued on page 4)

TABLE I. (continued) - page 4

<u>Property* (abbrev.)</u>	<u>Polychlorotri- fluoroethylene (Kel-F)</u>	<u>Polytetrafluoro- ethylene (Teflon)</u>	<u>Polyamide (Nylon)</u>
WATER			
Perm.	0.00	0.00	0.3-1.8
Absorp.	0.00	0.00	1.0-1.5
TEMP.			
Flow	420		
Max.	390	500	180-350
Min.	-80	-200	-60
Seal	415-450		
SOIL			
Acid	Excellent	Excellent	Poor
Base	Excellent	Excellent	Excellent
Salt	Excellent	Excellent	Fair to Good
Fungi	Good	Good	Good
Rodents			
WEATHER			
Oxygen +UV	Excellent	Excellent	Good
STRENGTH			
Tensile	6300-6600	1500-3500	9000
Elong.	90-200	100-300	Orients
Burst	42 (2 mils)		
Fold			
TOUGHNESS			
Abrasion			
Puncture			
Tear, g	200-350	10-100	
" , lb/in.			
ELEC. RESIST.			
Vol. resist.	10 ¹⁸	10 ¹⁹	5x10 ¹³
SPEC. GRAV.	2.1	2.1-2.2	1.1
COST			
Per lb.		10.00	1.43
Yield	12000	12800	24000
1000 sq. in.		0.78	0.060

*See first page of table for full designation.

(continued on page 5)

TABLE I. (continued) - page 5

<u>Property*</u> <u>(abbrev.)</u>	<u>Polystyrene</u>	<u>Acrylonitrile - Styrene Copolymer</u>	<u>Polymethyl Methacrylate</u>
WATER			
Perm.	0.5-0.7	0.4-0.5	0.5
Absorp.	Nil		0.3-0.4
TEMP.			
Flow	220-250		255-305
Max.	175-200	185	155-190
Min.	-50 to -70	-60	
Seal	220-300		
SOIL			
Acid	Good	Good	Good
Base	Excellent	Excellent	Good
Salt	Very good	Very good	Good
Fungi	Good		Good
Rodents			
WEATHER			
Oxygen +UV	Good	Excellent	Excellent
STRENGTH			
Tensile	7100-12100	10000-15000	8200-8800
Elong.	3-10		4-12
Burst			
Fold			
TOUGHNESS			
Abrasion			
Puncture			
Tear, g.			
" , lb/in.	270-495		340-380
ELEC. RESIST.			
Vol. resist.	10 ¹⁷ -10 ¹⁹		>10 ¹⁴
SPEC. GRAV.	1.05-1.08		1.18-1.19
COST			
Per lb.	0.35		0.55
Yield	26100	25400	23400
1000 sq. in.	0.013		0.023

*See first page of table for full designation.

(continued on page 6)

TABLE I. (concluded) - page 6

FOOTNOTES:

- ^aSources of information are indicated by the following references to the bibliography: (2,10,13,22,24,34,39,42,43,57,58,59,60,71,89,93,96,97,98).
- ^bUnless otherwise indicated.
- ^cExpressed in grams per 24 hours per square meter per millimeter thickness at a pressure differential of 1 centimeter of mercury ($\text{g}/24\text{hr}/\text{m}^2/\text{mm}/\text{cm Hg}$).
- ^dSpecific information on individual materials not available. See text for a general discussion of the problem.
- ^eExpressed in Mullen Points, for a 1-mil thick film.
- ^fCost figures are the latest conveniently available at time of survey, and usually are as of January 1958. In view of changing costs, especially for newer materials, current manufacturers' price lists should be consulted.
- ^gTests made with Schopper Bending Endurance Tester, using 1-mil thick film unless otherwise noted.
- ^hOther A.S.T.M. test methods, of interest but not utilized directly for the data given here, are discussed in the text and referred to in the bibliography.
- ⁱElmendorf test; gives pull required to continue tear of 1-mil thick film after starting.
- ^jSPI-ASTM static weighing method; yields pounds of force required to tear through a 1-inch thick film.
- ^kProperties are for the molded resin; data for films not available but should be similar.
- ^lWater permeability of polycarbonate resin is expressed in $\text{g}/\text{cm}/\text{hr}/\text{cm}^2/\text{mm Hg}$. (cf., footnote "c").

U. S. DEPARTMENT OF COMMERCE

Sinclair Weeks, *Secretary*

NATIONAL BUREAU OF STANDARDS

A. V. Astin, *Director*



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